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We consider a model for leptogenesis in which all the relevant physics is accessible in collider experiments. This requires a moderate extension of the standard model which generates small neutrino masses via TeV scale right-handed neutrinos. The necessary Sakharov criteria are satisfied in such a way that all existing experimental constraints are satisfied. We demonstrate how the requisite baryon to entropy ratio is generated, and discuss some possible experimental signatures of the model.

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The discovery of neutrino masses and mixing, reported by the Super-Kamiokande [1] and SNO [2] experiments, is an exciting example of the symbiosis between particle physics and cosmology. One interesting consequence of this discovery for cosmology is the possibility of generating the baryon asymmetry of the universe through leptogenesis via the decays of right-handed neutrinos (for reviews see [3]). However, one drawback of this approach is its inaccessibility to independent collider tests. This is because, in typical models, the masses of the right-handed neutrinos must be of order 10^{10} GeV in order that realistic Majorana masses for left-handed neutrinos be generated by the seesaw mechanism [4]. In this letter we describe a realistic model in which leptogenesis is efficient, and the required right-handed neutrinos need only have TeV-scale masses. This model is therefore a candidate for generating the baryon asymmetry of the universe (BAU), which may be directly tested in upcoming experiments.

Leptogenesis as a precursor to baryogenesis works because the $SU(2)_L$ sphaleron configurations which violate both baryon number (B) and lepton number (L), nevertheless conserve the combination $B-L$. Thus, the baryon asymmetry may be generated from an existing lepton asymmetry. Indeed, an analysis [5] of the chemical potentials in the standard model yields a relation between the baryon asymmetry

$$\eta_B = \frac{n_b - n_{\overline{b}}}{n_s} , \tag{1}$$

where $n_{b(\bar{b})}$ is the number density of (anti)baryons and n_s is the entropy density, and the corresponding B-L asymmetry, η_{B-L} given by

$$\eta_B = \frac{28}{79}\eta_{(B-L)_P} , \tag{2}$$

where $(B-L)_P$ is the primordial lepton asymmetry generated above the electroweak scale. It is the baryon asymmetry that is constrained by primordial nucleosynthesis to be $\eta_B \sim 10^{-10}$.

One important way in which leptons may be produced is by the out of equilibrium decay of heavy right handed Majorana neutrinos N_R. Once this asymmetry is produced it is then partially converted to a baryonic one.

In order that such an asymmetry survive, it is essential that $B-L$ violating processes be out of equilibrium after the leptons are produced. This yields a constraint on the masses of the right handed Majorana neutrinos, and hence on the left-handed neutrino masses. Consider the $\Delta L = 2$ process

$$\nu_L + \nu_L \longrightarrow \Phi_{SM} + \Phi_{SM} \ , \tag{3}$$

where ν_L are left-handed neutrinos and Φ_{SM} is the standard model Higgs field, occurring at the temperature $T \approx 100$ GeV. By imposing the out of equilibrium condition we obtain the constraint [6]

$$m_\nu < 50keV \ . \tag{4}$$

A stronger bound is obtained by requiring that the rate of the lepton violating interactions, for example

$$W^{\pm} + W^{\pm} \longrightarrow e^{\pm} + e^{\pm} \ , \tag{5}$$

mediated by virtual left handed Majorana neutrino exchange, be smaller that the expansion rate of the universe at temperature $T = M_W$. This yields the constraint $m_\nu < 20$ keV [7].

Note that this constraint is independent of the existence of right handed neutrinos or triplet higgs fields. It is a result of the effective interaction after integrating out the heavy fields, and it applies to every element of the mass matrix.

In this paper, we discuss the possibility of generating the baryon asymmetry of the universe (BAU) via leptogenesis at the TeV scale. We utilize a recently proposed model [8] for neutrino masses, in which the right handed Majorana masses are of order 10 TeV. We extend the standard model by adding three right handed neutrinos N_{R_α} and two new charged higgs fields S_1^+ and S_2^+, which are singlets under $SU(2)_L$. The interaction of S_1 and S_2 with the standard model fermions is given by:

$$\mathcal{L}_{int} = f_{\alpha\beta} L_\alpha^T C i\tau_2 L_\beta S_1^+ + g_{\alpha\beta} l_{R_\alpha}^T C N_{R_\beta} S_2^+ + \text{h.c} \ , \tag{6}$$

where α, β denote generation indices. Here L is the left-handed lepton doublet, l_{R_α} are the right-handed charged leptons and C is the charge-conjugation matrix. The Yukawa couplings $f_{\alpha\beta}$ are antisymmetric in α and β, while $g_{\alpha\beta}$ are arbitrary. We will demand that both S_1^+ and S_2^+ carry lepton number $L = -2$ so that the above interactions conserve lepton number. The standard model higgs doublet Φ_{SM} couples to the right handed neutrino and lepton doublets, which leads to a tree level neutrino Dirac mass. In this case unnatural fine tuning is needed. To forbid such coupling we impose a discrete symmetry Z_2 acting as

$$
\begin{aligned}
(L_\alpha, \Phi_{SM}, S_1^+) &\longrightarrow (L_\alpha, \Phi_{SM}, S_1^+) \\
(N_{R_\alpha}, S_2^+) &\longrightarrow -(N_{R_\alpha}, S_2^+) \ .
\end{aligned}
\tag{7}
$$

If this Z_2 symmetry is exact, the neutrinos will be massless. We therefore introduce the soft symmetry-breaking term

$$
\delta V = \kappa S_1 S_2^+ + \mathrm{h.c} \ . \tag{8}
$$

This term is crucial for generating a calculable Dirac mass term at one loop level (see Fig 1).

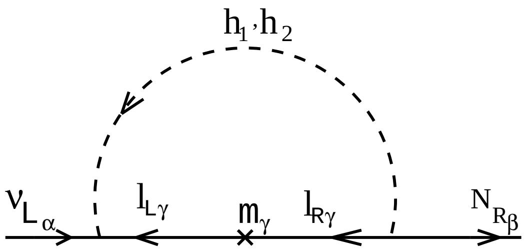

FIG. 1. A one-loop diagram generating Dirac masses for the neutrinos.

The induced Yukawa coupling is given by:

$$
\lambda_{\alpha\beta} = \frac{1}{64\pi^2} g_{\alpha\gamma} \frac{m_\gamma}{v} f_{\gamma\beta} \sin(2\theta) \ln\left(\frac{M_{S_2}}{M_{S_1}}\right) \tag{9}
$$

where m_γ are the charged lepton masses, v is the vacuum expectation value (VEV) of the standard model higgs doublet, M_{S_1} and M_{S_2} are the masses of the physical charged higgs fields, and $\sin(2\theta)$ is the mixing angle between S_1 and S_2 given by:

$$
\sin(2\theta) = \frac{2\kappa}{\sqrt{4\kappa^2 + (M_{S_2} - M_{S_1})}} \tag{10}
$$

Note that the Yukawa couplings in this model are naturally small. Without any fine tuning of the parameters $f_{\alpha\beta}$, $g_{\alpha\beta}$ it is simple to obtain $\lambda \sim 10^{-5}$. For right-handed neutrino masses $M_{R_\alpha} \sim 10$ TeV note also that Majorana masses for the left-handed neutrinos $m_\nu \leq 0.1$ eV are generated via the seesaw mechanism. A detailed analysis of the neutrino masses and mixing in this model can be found in ref. [8].

Now let us turn to the issue of baryogenesis. As we mentioned above, the baryon asymmetry may be generated by a lepton asymmetry. The first step in demonstrating how this occurs is to identify the lepton number violating decays. It is usual to consider the decay of the heavy right handed neutrinos N_{R_α} or of at least two heavy higgs triplets (denoted by $\Delta_{1,2}$).

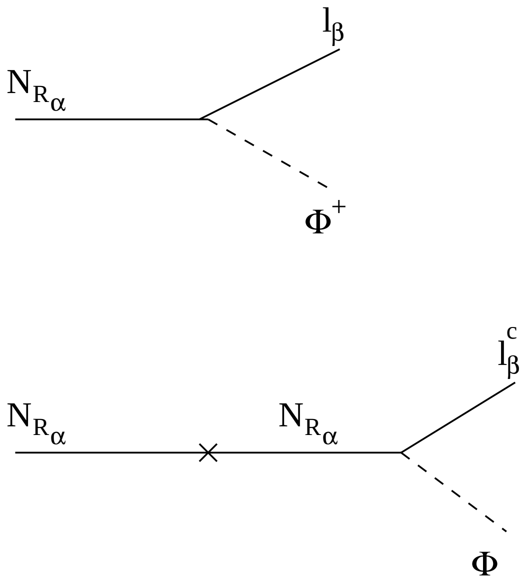

FIG. 2. Vertex and self energy diagrams for N_R decay.

In most leptogenesis models N_{R_α} and $\Delta_{1,2}$ are constrained to be heavy in order to suppress the masses of the physical neutrinos, since the Dirac neutrino masses are of the order charged lepton or quark masses. In our model the situation is very different. Here the Yukawa couplings between the left-handed and the right-handed neutrinos vanish at tree level, and are instead induced at one loop. This ensures that they are naturally small and as a result N_{R_α} need not be particularly heavy.

The relevant decays are (see fig 2)

$$\begin{aligned} N_{R_\alpha} &\longrightarrow l_{\alpha_L} + \overline{\Phi} \\ N_{R_\alpha} &\longrightarrow l^C_{\alpha_L} + \Phi \quad , \end{aligned} \tag{11}$$

which lead to a violation of lepton number by two units.

We now move on to the origin of CP violation in our model. The couplings $f_{\alpha\beta}$ can be made real by making a phase redefinition on the left handed fields. This is the same freedom that ensures CP-conservation in the leptonic sector of the Zee model [9]. However in our model the couplings $g_{\alpha\beta}$ may be complex, and therefore the last term in (6) is generically a source of CP violation in the leptonic sector. Despite this, it is well-known that CPT-invariance implies that the asymmetry in the decay rates vanishes at tree level.

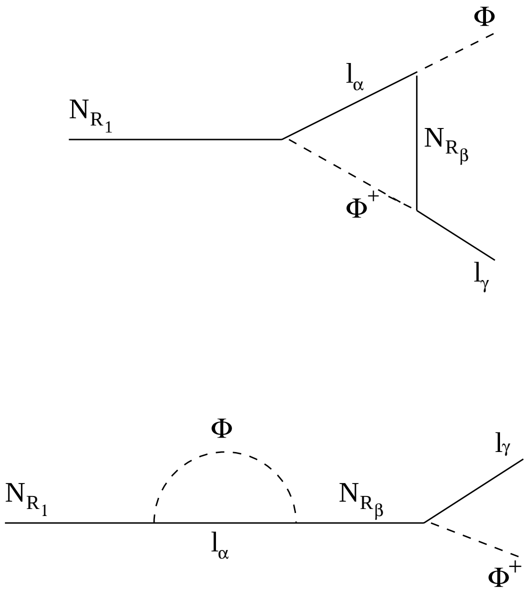

FIG. 3. Lepton number violating decays. The right-handed neutrino decays to leptons and antileptons.

Nevertheless, a non-zero asymmetry is generated through the interference between the tree level diagram and the one loop diagrams. Let us first consider the vertex correction and the wave function renormalization of N_{R_1} as in fig (3). The CP asymmetry generated from the interference of these diagrams may be estimated as

$$\epsilon \simeq \lambda^2 \left(\frac{M_{R_1}}{M_{R_2}} \right) , \tag{12}$$

where M_{R_1} is the mass of the lightest right-handed neutrino, and M_{R_2} is the mass of the next heaviest. In this case the lepton asymmetry generated is

$$\eta_L < 10^{-13} \left(\frac{\lambda}{10^{-5}} \right)^2 , \tag{13}$$

which implies that the baryon asymmetry of the universe is highly suppressed for $\lambda \simeq 10^{-5}$.

However, consider the self-energy diagram in which, instead of the standard model higgs field and the left-handed lepton, we have the charged higgs singlet S_2. In this case the right-handed charged lepton is the most dominant contribution in the interference with the tree level diagram because the couplings $g_{\alpha\beta}$ can be much larger than the Yukawa couplings $\lambda_{\alpha\beta}$.

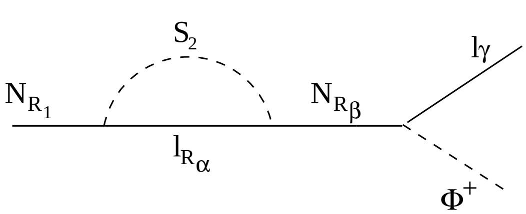

FIG. 4. Self energy diagram due the charged higgs singlet.

Let us assume that the the Yukawa couplings in (6) are all of the same order, and that the two right handed neutrinos are almost degenerate. The CP asymmetry generated from the decays (11) results from the interference between the tree level diagrams and the one loop diagrams and is given by

$$\epsilon \simeq \frac{1}{16\pi} g^2 xy \sin\delta \ , \tag{14}$$

where g is the Yukawa coupling of the right handed neutrinos with the charged singlet higgs S_2 and $\delta = \arg(g^2)$. The parameters x and y are defined by:

$$x = \frac{M_{R_1}}{M_{R_2} - M_{R_1}}$$
$$y = 1 - \left(\frac{M_{S_2}}{M_{R_1}}\right)^2 \tag{15}$$

Note that the CP asymmetry gets enhanced when the right handed neutrinos are almost degenerate [10]. Of course if they are exactly degenerate the CP asymmetry vanishes, because in this case the relative phase between the degenerate states can be rotated away. This is why we need at least two non-degenerate right handed neutrino states. The same considerations apply for leptogenesis via the decay of the higgs triplet [11].

The parameter y can lead to a suppression when $M_{S_2} \simeq M_{R_1}$. Indeed one needs y to be tiny in order to suppress the decay $S_2 \longrightarrow l_{R_\alpha} + N_{R_\alpha}$, otherwise it will be rapid enough to wash out the baryon asymmetry generated at $T \simeq M_{R_1}$.

Now consider the required departure from thermal equilibrium in this model. The relevant quantity parameterizing this is the ratio

$$K = \frac{\Gamma_{N_R}}{H} \ , \tag{16}$$

where Γ_{N_R} is the decay rate of N_{R_1}, and $H = \sqrt{1.7} g_* T^2/M_P$ is the expansion rate of the universe, with $M_P \simeq 10^{19} GeV$ the Planck mass. If $K << 1$, then the system is far from equilibrium and the lepton asymmetry will be $\eta_L \simeq \frac{\epsilon}{g_*}$. However if $K >> 1$, then the baryon asymmetry will be suppressed by a factor [12],

$$D \simeq \begin{cases} \sqrt{0.1K} \exp\left[-\frac{4}{3}(0.1K)^{\frac{1}{4}}\right] & \text{for } K \geq 10^6 \\ \frac{1}{K(\ln K)^{0.6}} & \text{for } 10 < K \leq 10^6 \\ \frac{1}{2K} & \text{for } 1 < K < 10 \end{cases} \ . \tag{17}$$

In our case

$$K = \frac{\lambda\lambda^+}{16\pi} \frac{M_P}{1.7\sqrt{g_*} M} \tag{18}$$

and for $M_{R_1} \sim 10 TeV$ the dilution factor is $D \sim 3 \times 10^{-3}$. Taking this into account, the baryon asymmetry generated by our model may be estimated as

$$\eta \simeq 10^{-6} x y g^2 \sin\delta \ . \tag{19}$$

Although we may choose x to be as large as 10^4, over a wide range of Yukawa couplings $f_{\alpha\beta}$ and $g_{\alpha\beta}$ reasonable values of the parameters involved are $x \sim 10^2$, $y \sim 10^{-5}$–10^{-4} and $g^2 \sin\delta \sim 10^{-2}$. Using these values we obtain $\eta \sim 10^{-11} - 10^{-10}$, which is in the range required for successful primordial nucleosynthesis.

Now, as we have advertised, a very attractive feature of this model is its accessibility to experimental tests. As a specific example, consider the scattering of polarized beams of right-handed electrons. One observable outcome of this would be the production of charged singlet fields S_2^-, mediated by the right-handed neutrinos

$$e_R + e_R \longrightarrow S_2^- + S_2^- \ . \tag{20}$$

This prediction depends crucially on how low the mass of the right-handed neutrino is allowed to be in this model, since the Majorana mass insertion appears explicitly in the relevant Feynman diagram (see fig 5).

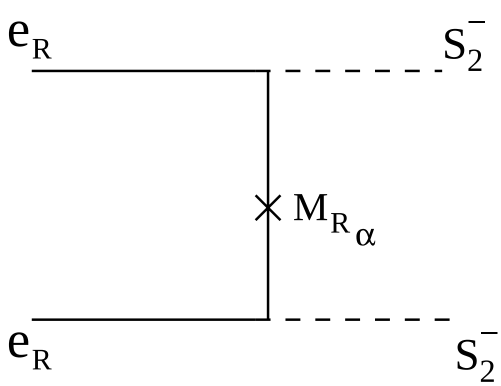

FIG. 5. The observable process $e_R + e_R \longrightarrow S_2^- + S_2^-$, predicted by the model.

In this letter we have described how leptogenesis, and hence baryogenesis, can occur quite naturally in an existing particle physics model. The model involves a modest extension of the standard electroweak theory, required to generate naturally low Dirac masses for the left-handed neutrinos. In this sense, the generation of the baryon asymmetry of the universe is natural in this model. Leptogenesis is traditionally thought to occur at the relatively high scale of 10^{10} GeV. However, a very attractive feature of the model presented here is that only scales of less than or of order 10 TeV are required. This means that it is feasible to test this model in collider experiments, perhaps at a high-center of mass energy e^+, e^- machine.

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